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United States Midwest Soil and Weather Conditions Influence Anaerobic Potentially Mineralizable Nitrogen

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Nitrogen provided to crops through mineralization is an important factor in N management guidelines. Understanding of the interactive effects of soil and weather conditions on N mineralization needs to be improved. Relationships between anaerobic potentially mineralizable N (PMN_{an}) and soil and weather conditions were evaluated under the contrasting climates of eight US Midwestern states. Soil was sampled (0–30 cm) for PMN_{an} analysis before pre-plant N application (PP_{0N}) and at the V5 development stage from the pre-plant 0 ($V5_{0N}$) and 180 kg N ha^{-1} ($V5_{180N}$) rates and incubated for 7, 14, and 28 d. Even distribution of precipitation and warmer temperatures before soil sampling and greater soil organic matter (SOM) increased PMN_{an}. Soil properties, including total C, SOM, and total N, had the strongest relationships with PMN_{an} ($R^2 \leq 0.40$), followed by temperature ($R^2 \leq 0.20$) and precipitation ($R^2 \leq 0.18$) variables. The strength of the relationships between soil properties and PMN_{an} from PP_{0N}, $V5_{0N}$, and $V5_{180N}$ varied by ≤10%. Including soil and weather in the model greatly increased PMN_{an} predictability ($R^2 \leq 0.69$), demonstrating the interactive effect of soil and weather on N mineralization at different times during the growing season regardless of N fertilization. Delayed soil sampling ($V5_{0N}$) and sampling after fertilization ($V5_{180N}$) reduced PMN_{an} predictability. However, longer PMN_{an} incubations improved PMN_{an} predictability from both V5 soil samplings closer to the PMN_{an} predictability from PP_{0N}, indicating the potential of PMN_{an} from longer incubations to provide improved estimates of N mineralization when N fertilizer is applied.

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Core Ideas

- **Relationships between mineralization estimates taken with the PMN_{an} test and soil and weather conditions need to be improved.**
- **Soil sample timing and N fertilization minimally affected PMN_{an} predictability by soil and weather parameters.**
- **Soil properties predict PMN_{an} better than weather conditions.**
- **Soil and weather conditions combined explain up to 69% of the variability of PMN_{an}.**
- **Longer PMN_{an} incubations improve the relationship between soil and weather parameters and PMN_{an} after N fertilization.**

Abbreviations: AWDR, abundant and well-distributed rainfall; first-GDD, first day of the calendar year where temperatures were high enough to calculate a growing degree-day; GDD, growing degree-day; PMN_{an}, anaerobic potentially mineralizable nitrogen; PP, pre-plant; PP_{0N}, pre-plant soil sampling where 0 kg N ha^{-1} was applied at planting; SDI, Shannon diversity index; SOM, soil organic matter; $V5_{0N}$, V5 soil sampling where no N was applied at planting; $V5_{180N}$, V5 soil sampling where 180 kg N ha^{-1} was applied at planting.

Nitrogen is needed for optimal growth and development of crops. The ability of the soil to supply N to corn (*Zea mays* L.) can vary from 20 to 100% of crop N needs (Khan et al., 2001; Ros et al., 2011; Yost et al., 2012). This wide range in N mineralization potential demonstrates the need to better estimate the contribution of N mineralization to crop N requirements. An improvement in the estimate of N mineralization would likely lead to improved fertilizer N rate guidelines and fertilizer N use efficiency. This improvement in fertilizer N rate guidelines would lower the potential for underfertilization, which reduces yield and profit, and overfertilization, which also reduces profits and is associated with negative environmental effects (Ribaudo et al., 2011).

Although there are many soil biological and chemical indices that are used to estimate N mineralization (Schomberg et al., 2009; Stanford and Smith, 1972; Wade et al., 2016), the two standard biological mineralization indices are the aerobic (Stanford and Smith, 1972) and anaerobic potentially mineralizable N (PMN_{an}) (Keeney and Bremner, 1966; Waring and Bremner, 1964) tests. The aerobic test is traditionally considered the benchmark mineralization test by which other tests are compared. However, the aerobic and PMN_{an} tests have been shown to be highly correlated in both forest and agricultural soils (Mariano et al., 2013; Smith et al., 1981; Waring and Bremner, 1964). The PMN_{an} test is now used more often for routine analysis because it is cheaper, has a shorter turnaround, and measures only NH_4–N (Bundy and Meisinger, 1994; Waring and Bremner, 1964). The PMN_{an} test quantifies N mineralization by incubating saturated soils at 40°C for 7 d and measuring the net amount of NH_4–N produced.

The PMN_{an} test has been successfully used as an N mineralization estimate in Argentina to improve relative yield predictability and the accuracy of soil tests, such as the pre-plant and pre-sidedress nitrate tests, which are used to make N fertilizer application decisions (Orcellet et al., 2017; Sainz Rozas et al., 2008). Other studies in the northwestern and southeastern areas of the United States have successfully related PMN_{an} to the N response of winter wheat and the economic optimal N rate of corn (Christensen et al., 1999; Williams et al., 2007). These results indicate that PMN_{an} has the potential to improve the accuracy of N recommendation systems in the US Midwest. An understanding of the variability of PMN_{an} in the contrasting soil and weather conditions of the US Midwest would aid in determining the potential use of PMN_{an} as an estimate of N mineralization to improve the accuracy of N recommendations.

The amount of N mineralized in a growing season is dependent on the size and quality of the organic N pool (Sierra, 1992; Wu et al., 2008). The rate at which the organic N pool then decomposes depends on air and soil temperature, soil moisture (Cabrera et al., 2005; Kuzyakova et al., 2006; Wu et al., 2008), and tillage (Beyaert and Voroney, 2011; Mikha et al., 2006). Many studies have examined the effects of crop rotation (Carrington et al., 2012; Gentile et al., 2011; Grandy and Neff, 2008; Parton et al., 2007), tillage (Beyaert and Voroney, 2011; Mikha et al., 2006), and cover cropping practices (Kuo and Sainju, 1998; Melkonian et al., 2017) on N mineralization, but fewer have examined the effect of soil properties and weather patterns on N mineralization.

In previous studies, soil properties such as cation exchange capacity, total organic C, and total N were correlated to mineralizable N (Fox and Piekielek, 1984; Narteh and Sahrawat, 1997; Schomberg et al., 2009; Soon et al., 2007). In contrast, other studies found no relationship between N mineralization and total organic C or soil organic matter (SOM) (Mariano et al., 2013; Reussi Calvo et al., 2013; Sainz Rozas et al., 2008). Soil texture class has also been shown to have a relationship with N mineralization, with sand having a negative relationship and clay a positive relationship (Dessureault-Rompré et al., 2010; Ladd et al., 1996). Greater clay content can be associated with greater N mineralization because of its ability to physically protect organic matter from decomposition (Hassink et al., 1993). In contrast, soil microbial biomass is typically more active in a coarse-textured soil relative to a fine-textured soil (Franzluebbers et al., 1996). Overall, these soil properties are related to the structure of the soil and its ability to exchange gas and retain moisture that is needed for the microbially mediated process of N mineralization (Van Veen and Kuikman, 1990)

Weather is also an important factor in N mineralization. The amount of N mineralization has been shown to increase with temperature in both laboratory and field studies (Fernández et al., 2017; Kuzyakova et al., 2006; Sierra, 1996; Wu et al., 2008). Precipitation also influences N mineralization. Specifically, low precipitation and soil moisture are often related to differing patterns and lower amounts of N mineralization (Kuzyakova et al., 2006). Precipitation events that rewet the soil throughout the growing season also stimulate increases in N mineralization more so than a single precipitation event (Murphy et al., 1998; Wu et al., 2008). Furthermore, N mineralization has been found to be at its highest when temperatures are maximal and soil moisture is slowly decreasing (Kuzyakova et al., 2006). There is also an interactive effect of temperature and precipitation on N mineralization that varies by soil texture and location of the soil in the landscape. For example, soils with low organic matter and clay content have the strongest N mineralization response to temperature and precipitation changes. On the other hand, soils with greater clay content and organic matter have shown weaker responses to changes in temperature and precipitation, likely due to the ability of clay and organic matter to buffer the influence of changes in environmental conditions (Kuzyakova et al., 2006).

Few studies have examined the influence of weather/climate and soil texture across a large geographical area to determine their influence on mineralization. One such study that spanned across North America determined that the macroclimate (temperature and precipitation regime) had a significant effect on the amount of SOM that was available for decomposition (Franzluebbers et al., 2001). In addition, greater mean annual temperatures resulted in more mineralization, whereas the influence of precipitation on mineralization varied based on the temperature regime. In a study with soils across Canada, Dessureault-Rompré et al. (2010) determined soil properties alone can explain up to 40% of the variability in mineralization, whereas climate predictors explained only up to 24%. By combining soil and climate parameters in a multiple regression, the explained variation in mineralization increased to 63%. The US Midwestern Cornbelt region has varying weather and soil conditions that likely influence N mineralization. For example, as summarized by Kitchen et al. (2017), mean annual precipitation increases from the northwest (223–519 mm) to the southeast (92–1157 mm), and mean annual temperature increases from the north (−0.7 to 5.4°C) to the south (13.9–18.2°C). These temperature differences lead to a growing season duration of ∼90 d in the north and up to 120 d in the south. The soils in the US Midwest region that are important to agriculture are diverse and dominated by Alfisols, Mollisols, and Entisols. However, the relationships between PMN_{an} and these contrasting soil texture and weather conditions in the US Midwestern Cornbelt region alone or combined have not been studied at length.

The relationship between soil and weather parameters and mineralization values have typically been examined on soil samples taken in the spring before fertilization. However, it has recently been shown that soil sample collection timing, N fertilization, and the incubation period of the PMN_{an} test can affect PMN_{an} by increasing or decreasing it, depending on soil properties and the weather conditions before sampling (Clark, 2018; Culman et al., 2013). The relationship between soil properties and weather conditions and PMN_{an} from different sample timings, N fertilization rates, and different incubation lengths has not been investigated. The influence of N fertilization and soil sample collection timing on PMN_{an} is especially important in the corn production areas of the US Midwest. Nitrogen fertilizer application is important because it is applied to most corn production fields and has been reported to alter the amount and variability of N mineralization, depending on the quality of the organic N and soil texture (Chen et al., 2014; Conde et al., 2005; Fernández et al., 2017; Ma et al., 1999). This increased variability may lower the utility of the PMN_{an} test obtained from soil samples taken before fertilization to provide N recommendations when fertilizer is either all applied near-planting or split into two or more applications throughout the season. Soil sample timing is important because N mineralized in the early spring is highly susceptible to loss in the US Midwest from denitrification and leaching processes due to greater spring precipitation and less N uptake by corn until it reaches the V5-V6 development stage (Randall and Vetsch, 2005; Ritchie et al., 1996; Struffert et al., 2016). This later uptake timing of corn indicates that an N mineralization estimate closer to the high N uptake period of corn may be a more accurate estimate of N available for uptake by the corn crop. Thus, the objective of this research was to determine the effect of soil and weather information across a range of environmental conditions within the US Midwestern Corn Belt on PMN_{an} predictability.

MATERIALS AND METHODS

Experimental Design

Thirty-two study sites were selected in eight US Midwestern states (Illinois, Indiana, Iowa, Minnesota, Missouri, Nebraska, North Dakota, and Wisconsin). Maps and tables with information on soil classification and physical and chemical characteristics, precipitation, temperature, and other site descriptions along with details on the uniform treatments, measurement methodologies, and agronomic practices used across all sites were presented by Kitchen et al. (2017). A standard research protocol was used at all experimental sites that included the same treatments and measurement methodology. The research protocol, along with specific details regarding agronomic practices, is described in Kitchen et al. (2017). Briefly, two sites were selected in each state in 2014 and 2015 (32 site-years total). A randomized complete block design with four replications was used at each experimental site. Nitrogen rates selected for this study consisted of an unfertilized check and an N rate of 180 kg N ha^{-1} applied at planting, which was considered the N rate that would typically optimize corn grain yield. These two N rates were a subset of the eight N rates applied in this study (0–315 kg N ha^{-1} in increments of 45 kg N ha^{-1} applied as a single application near planting and split between two timings). Nitrogen as ammonium nitrate (34–0–0, N–P–K) was broadcast-applied and left on the soil surface.

Soil Sampling

At each site before planting and fertilization, two soil cores were obtained from each replication (120-cm depth; 3.8–4.0 cm i.d.) and divided by horizons to measure physical and chemical properties. These soil properties included a taxonomic description, bulk density (bulk density–measured), total C, total organic C, SOM, total N, cation exchange capacity, and pH (1:1 soil/water pH and 1:1 soil/salt [1 M KCl] pH) as described in Kitchen et al. (2017). Soil texture and SOM measurements were used to calculate Saxton bulk density (bulk density-Saxton) (Saxton and Rawls, 2006). We calculated weighted averages for the various soil measurements using the depth of each horizon within the 0- to 30-cm soil depth.

The PP_{0N} soil samples were obtained using a 10-core (0- to 30-cm, 30- to 60-cm, and 60- to 90-cm soil depths; 1.9 to 4.0 cm i.d.) composite soil sample before planting and fertilization. At the V5 corn development stage, a six-core composite (0 to 30- and 30 to 60-cm soil depths; 1.9 cm i.d.) soil sample was obtained from the 0 ($V5_{0N}$) and at-planting 180 ($V5_{180N}$) kg N ha^{-1} treatments. All soil samples were dried (≤32°C) and ground to pass through a 2-mm sieve. Soil NO_3–N was extracted using 0.2 M KCl (Saha et al., 2018) and quantified by the cadmium reduction method (Gelderman and Beegle, 2015) with a modified Technicon AutoAnalyzer (SEAL Analytical, Inc.). Only the surface soils (0–30 cm depth in this study) were analyzed for PMN_{an} to maintain consistency with depth used when the PMN_{an} test was originally developed (Bundy and Meisinger, 1994).

To determine PMN_{an}, 20 mL of ultrapure water was placed on top of 4.0 g of soil in 50-mL Falcon tubes (Corning Inc.). The

Table 1. Weather variables used and their definitions.

Weather parameter	Definition
Mean minimum temperature	Tmin = minimum daily temperature
Mean maximum temperature	Tmax = maximum daily temperature
Mean temperature	MeanTemp = (Tmax + Tmin)/2
Growing degree-days	GDD = [(Tmax + Tmin)/2] – 10°C, where Tmax = Tmax if 10 ≤ Tmax ≤ 30, if Tmax ≤ 10 then Tmax = 10, if Tmax ≥ 30 then Tmax = 30; Tmin = the minimum daily temperature if Tmin ≥ 10, if Tmin ≤ 10 then Tmin = 10; all temperatures measured in °C
Sum of precipitation	SP = Σ(Rain), where rain is the daily precipitation (mm)
Mean precipitation	MaxP = SP/n, where n is the number of days in that period
Maximum precipitation	MaxP = maximum amount of rain in a single day in that period
Shannon diversity index	SDI = [−Σpi ln(pi)]/ln(n), where pi = rain/SP is the fraction of daily precipitation relative to the total precipitation in a given time period, and n is the number of days in that period. SDI = 1 implies complete evenness (i.e., equal amounts of precipitation in each day of the period); SDI = 0 implies complete unevenness (i.e., all rain in 1 d)
Abundant and well-distributed rainfall	AWDR = SP(SDI)

tubes were capped and subjected to incubation for 7, 14, and 28 d at 40°C (Keeney and Bremner, 1966). Twenty milliliters of 4 M KCl was added to the solution after incubation for a final extractant concentration of 2 M KCl, and samples were shaken for 30 min. The solution was then passed through a washed 0.45-μm syringe filter disk and stored in a microtube at −80°C until NH_4–N analysis. The Berthelot method was then used to determine extracted NH_4–N (Rhine et al., 1998) using a Glomax-Multi Detection System plate reader (Promega Biosystems, Inc.). The initial NH_4–N value before incubation was also determined for each soil sample following the above extraction procedure with 2 M KCl and subtracted from the NH_4–N postincubation value to obtain net NH_4–N produced or PMN_{an}.

Weather

Weather data were collected during the growing season from each experimental site with a HOBO U30 automatic weather station (Onset Computer Corp.). Precipitation and air temperature measurements at ∼1.8 m above the ground were recorded every 5 min and used to calculate the daily minimum, maximum, and mean air temperatures and the daily cumulative precipitation. Water provided as irrigation in four of the 32 experimental sites was treated as natural precipitation in these calculations. These daily weather measurements were quality checked by comparing the weather station measurements against interpolated temperature data from Multi-Radar/Multi-Sensor precipitation data (The National Severe Storms Lab, NOAA) as described in Kitchen et al. (2017). Table 1 shows the equations used to calculate growing degree-days (GDDs), mean precipitation, Shannon diversity index (SDI) following Bronikowski and Webb (1996), and abundant and well-distributed rainfall (AWDR) following Tremblay et al. (2012) for different periods during the growing season. The first GDD of the year (first-GDD) was calculated by determining the first day of the calendar year where temperatures were high enough to calculate a GDD.

Statistical Analysis

Statistical analyses were conducted with SAS software version 9.4 (SAS Institute Inc.). Correlations within soil, precipitation, and temperature variables were determined using PROC CORR. The relationship between PMN_{an} and weather measurements and site characteristics were determined using PROC REG. Linear and quadratic models were evaluated. The highest-order model with a P value ≤0.05 was selected. The R^2 value from the simple, linear model was displayed if both linear and quadratic models were not significant ($\alpha = 0.05$). The R^2 values of these models were compared to determine whether altering PMN_{an} sample timing (PP_{0N} vs. $V5_{0N}$) or N rate ($V5_{0N}$ vs. $V5_{180N}$) or increasing incubation time (7, 14, and 28 d) improved the relationship between PMN_{an} and soil and weather variables.

The stepwise, forward, backward, and Mallows' C_p (Mallows, 1973) selection methods within the REG procedure were used to determine the best combination of soil, precipitation, and temperature variables to predict PMN_{an} and how frequently each of these variables was selected. The contributions of temperature and precipitation at defined time intervals were compared for their ability to improve the prediction of PMN_{an}. Two intervals were evaluated for the PP_{0N} soil sampling, and four intervals were evaluated for the V5 soil sampling. The time intervals for the PP_{0N} sampling were (i) first-GDD to PP_{0N} and (ii) 30 d before PP_{0N}. The time intervals for the V5 sample timings were (i) first-GDD to V5, (ii) 30 d before PP_{0N} to V5, (iii) PP_{0N} to V5, and (iv) 30 d before V5. Only the weather period for each PMN_{an} sample timing (pre-plant and V5) that contributed the most to predicting PMN_{an} is shown in this paper.

RESULTS AND DISCUSSION

Collecting soil samples from fields across eight states in the US Midwest resulted in a wide range of soil properties (Table 2) and weather conditions before soil sampling (Table 3). These differences in soil properties and weather conditions led to PMN_{an} values ranging from 0.2 to 99.9 mg N kg^{-1} for the 7-d incubations, 2.1 to 122.7 mg N kg^{-1} for the 14-d incubations, and 4.0 to 136.7 mg N kg^{-1} for the 28-d incubations. The PMN_{an} range of other studies in the United States (12–87 mg N kg^{-1}) fell within the approximate range of the values found in this study (Christensen and Mellbye, 2006; Fox and Piekielek, 1984). However, this study did have PMN_{an} values below those of these other studies, likely due to the low organic matter content of some of the soils evaluated in conjunction with the deeper sampling depth. The wide range in soil and weather conditions along with PMN_{an} created an optimal database to determine relationships between PMN_{an} and soil and weather parameters.

Relationship between Anaerobic Potentially Mineralizable N and Soil Properties

Soil properties, other than soil NO_3–N and NH_4–N, produced better relationships with PMN_{an} compared with weather variables (mean $R^2 = 0.19$; range, 0.03–0.41) (Table 4). Cation exchange capacity, total C, total organic C, SOM, total N, and bulk density were the soil properties that had the best relationships with PMN_{an} ($R^2 = 0.25$ when averaged across all PMN_{an} measurements). Except for bulk density, these properties had a positive relationship with PMN_{an}, likely because they directly or indirectly measure the size of the organic N pool, which influences mineralizable N (Cabrera et al., 2005; Mikha et al., 2006; O'Leary et al., 2002; Wu et al., 2008). Previous research has reported similar positive relationships between PMN_{an} and cation exchange capacity (Narteh and Sahrawat, 1997), total organic C (Fox and Piekielek, 1984; Narteh and Sahrawat, 1997; Schomberg et al., 2009; Soon et al., 2007), and total N (Fox and Piekielek, 1984; Soon et al., 2007; Schomberg et al., 2009), whereas others have reported no relationship between PMN_{an} and total organic C (Mariano et al., 2013; Sainz Rozas et al., 2008) or SOM (Reussi Calvo et al., 2013). The contrasting results among studies may be related to differences in the amount of mineral-associated C versus the particulate-organic C that makes up the total organic C content of soil (Reussi Calvo et al., 2013). Particulate-organic C is normally greater in coarse-textured soils (Divito et al., 2011) and has a better relationship with mineralizable N compared with mineral-associated organic C, which is predominant in fine-textured soils (Studdert et al., 2006). Thus, the inclusion of more coarse-textured soils in our study compared with other studies likely improved the relationship between PMN_{an} and total organic C. The lack of correlation between PMN_{an} and total organic C in some of these other studies may also be the result of

Table 2. Minimum, maximum, mean, standard deviation, and coefficient of variation of anaerobic potentially mineralizable N (PMN_{an}) and soil properties across 32 site-years.

Property†	Min.	Max.	Mean	SD	CV
PMN_{an}, mg N kg^{-1}					
PP_{0N}, 7 d	0.7	84.0	26.7	15.1	56.8
PP_{0N}, 14 d	2.4	94.5	37.8	18.9	50.0
PP_{0N}, 28 d	6.0	125.3	48.9	25.4	51.9
$V5_{0N}$, 7 d	0.2	99.9	28.3	15.0	53.1
$V5_{0N}$, 14 d	2.1	122.7	37.0	17.4	47.0
$V5_{0N}$, 28 d	4.0	136.7	48.5	23.2	47.8
$V5_{180N}$, 7 d	0.9	92.2	23.2	15.2	65.4
$V5_{180N}$, 14 d	6.9	109.9	32.4	17.5	53.9
$V5_{180N}$, 28 d	8.1	130.7	43.1	23.6	54.7
Soil properties					
Sand, %	2	93	26	25	95
Silt, %	4	79	50	19	39
Clay, %	2	61	24	11	47
BD-measured, g cm^{-3}	0.95	1.66	1.37	0.13	9.78
BD-Saxton, g cm^{-3}	1.07	1.60	1.34	0.13	9.98
TC, g kg^{-1}	4.4	55.5	14.6	7.6	51.8
TOC, g kg^{-1}	4.4	47.8	14.2	6.9	48.5
SOM, g kg^{-1}	7.7	71.0	25.7	10.0	38.9
Total N, g kg^{-1}	0.4	4.3	1.4	0.6	41.8
C/N, g kg^{-1}	7.2	12.7	10.0	1.0	10.4
CEC, cmol kg^{-1}	3	44	20	9	46
pH-salt	4.4	7.8	6.1	0.8	13.6
pH-water	5.1	8.8	6.7	0.8	11.4
Soil-N at PP_{0N}, mg kg^{-1}					
Ammonium 0–30 cm	3	19	8	4	44
Nitrate 0–30 cm	1	18	6	3	53
Nitrate 0–60 cm	1	12	5	2	42
Nitrate 0–90 cm	1	9	4	2	40
Soil-N at $V5_{0N}$, mg kg^{-1}					
Ammonium 0–30 cm	1	14	7	3	47
Nitrate 0–30 cm	3	27	8	4	58
Nitrate 0–60 cm	2	21	7	4	49
Soil-N at $V5_{180N}$, mg kg^{-1}					
Ammonium 0–30 cm	2	34	9	5	63
Nitrate 0–30 cm	7	75	32	12	38
Nitrate 0–60 cm	9	58	24	9	35

† BD, bulk density; CEC, cation exchange capacity; PP_{0N}, PMN_{an} from pre-plant soil sampling with 0 kg N ha^{-1}; SOM, soil organic matter; TC, total C; TOC, total organic C; $V5_{0N}$, PMN_{an} from V5 corn development stage with 0 kg N ha^{-1}; $V5_{180N}$, PMN_{an} from V5 corn development stage with 180 kg N ha^{-1} applied at planting.

Table 3. Minimum, maximum, mean, standard deviation, and coefficient of variation of precipitation and temperature conditions for the period of 30 d before pre-plant (PP) sampling time to PP and from the PP soil sampling time to the V5 corn development stage across 32 site-years.

	30 d before PP to PP					PP to V5				
Parameter†	Min.	Max.	Mean	SD	CV	Min.	Max.	Mean	SD	CV
Precipitation										
Maximum, mm	0.30	63	22	17	76	19	95	39	18	46
Sum of precipitation, mm	0.60	250	72	58	80	85	331	175	68	39
Mean, mm	0.02	8	2	2	80	2	5	3	0.6	17
SDI	0.05	0.7	0.5	0.2	34	0.5	0.7	0.6	0.05	8
AWDR	0.12	155	42	37	87	47	242	110	47	43
Temperature										
Mean maximum, °C	9	18	14	3	21	19	27	22	2	8
Mean minimum, °C	–7	7	0.5	4	903	6	13	10	2	1
Mean, °C	2	13	7	3	48	13	20	16	2	10
GDD	43	147	84	30	36	228	543	347	84	24

† AWDR, abundant and well-distributed rainfall; GDD, growing degree-day; SDI, Shannon diversity index.

large C/N ratios causing N to be immobilized instead of mineralized, leading to reduced correlations with PMN_{an} (Mariano et al., 2013). Unlike the previously discussed soil properties, bulk density had a negative relationship with PMN_{an} (Table 4) because soils with greater bulk densities in this study were sandy and had less SOM and total N (Table 5), which decreases mineralizable N potential (Dessureault-Rompré et al., 2010). Soils with greater bulk density can also reduce mineralization by limiting microbial access to organic N (Beare et al., 2009).

Soil texture properties (sand, silt, and clay) had a weaker relationship with PMN_{an} (average R^2 = 0.12) compared with the previously discussed soil properties (Table 4). Other studies have reported similarly poor relationships between PMN_{an} and sand, silt, and clay content (Dessureault-Rompré et al., 2010; Mariano et al., 2013). On average, the predictability of PMN_{an} was less for silt (R^2 = 0.05) relative to sand (R^2 = 0.13) and clay (R^2 = 0.15) because sand and clay, compared with silt content, relate better to total N and SOM (Table 5), which is strongly associated with PMN_{an} (Table 4). There was a positive relationship between PMN_{an} and clay and silt content because soils with greater silt and clay had more SOM (Table 5), which relates to greater PMN_{an} (Table 4). More SOM and potentially mineralizable N also occurred in soils with greater clay content because clay particles can physically protect organic N from microbial decomposition,

Table 4. Coefficients of determination of the anaerobic potentially mineralizable N soil test (PMN_{an}) from soil samples obtained before planting and N fertilizer application (PP_{0N}) and at the V5 development stage where zero ($V5_{0N}$) or 180 kg N ha^{-1} ($V5_{180N}$) was applied at planting and incubated for 7, 14, and 28 d as a function of soil properties, precipitation, and temperature variables across 32 site-years.

	PP_{0N}			$V5_{0N}$			$V5_{180N}$		
Variable†	**7 d**	**14 d**	**28 d**	**7 d**	**14 d**	**28 d**	**7 d**	**14 d**	**28 d**
	R^2								
Soil physical characteristics									
% Sand	0.13*N‡	0.21*N	0.20*	0.08*N	0.16*N, Q§	0.19*N	0.02	0.06*N	0.11*N
% Silt	0.05*	0.10*	0.08*	0.03	0.07*	0.09*	<0.01	0.01	0.03
% Clay	0.14*	0.18*	0.21*	0.12*	0.14*	0.20*	0.06*	0.14*	0.19*
BD-measured	0.20*N	0.20*N	0.26*N	0.14*N	0.16*N	0.26*N	0.09*N	0.14*N	0.23*N
BD-Saxton	0.19*N	0.28*N	0.29*N	0.22*N	0.24*N	0.36*N	0.15*N	0.24*N	0.34*N
Soil chemical characteristics									
TC	0.30*	0.29*Q	0.37*Q	0.17*	0.19*	0.24*	0.24*Q	0.29*	0.39*
TOC	0.31*	0.30*Q	0.38*Q	0.16*	0.18*	0.25*	0.24*N, Q	0.29*	0.40*
SOM	0.29*	0.30*	0.37*Q	0.12*	0.16*	0.25*	0.22*N, Q	0.30*N, Q	0.37*
TN	0.33*	0.30*	0.40*Q	0.17*	0.20*	0.27*	0.22*N, Q	0.26*	0.38*
C/N	0.10*	0.08*	0.11*	0.05*	0.03*	0.05*	0.12*	0.15*	0.17*
CEC	0.23*	0.22*	0.26*	0.16*	0.18*	0.24*	0.12*	0.22*	0.28*
pH-salt	0.14*	0.06*	0.06*	0.22*N, Q	0.17*N,Q	0.16*N, Q	0.17*N, Q	0.18*N, Q	0.19*N, Q
pH-water	0.13*	0.05*	0.05*	0.08*N, Q	0.08*N, Q	0.06*N, Q	0.09*	0.10*N, Q	0.10*N, Q
Inorganic N¶									
NH_4–N§ 0–30 cm	0.06*N, Q	0.01	0.07*	0.01	0.06*Q	0.08*Q	<0.01	0.04*Q	0.03
NO_3–N§ 0–30 cm	0.01	0.02	0.01	<0.00	0.01	0.02	0.02	<0.01	<0.01
NO_3–N 0–60 cm	0.04*	0.06*	0.05*	0.01	0.03	0.04*	0.01	<0.01	<0.01
NO_3–N 0–90 cm	0.07*	0.08*	0.06*						
Precipitation#									
Maximum	0.02	0.03	0.02	0.05*N	<0.01	<0.01	0.01	0.01	<0.01
Sum of precipitation	0.01	0.01	0.01	0.13*Q	0.16*Q	0.16*Q	< 0.01	0.08*Q	0.08*Q
Mean	0.01	0.01	0.01	0.01	<0.01	<0.01	0.05*N, Q	0.05*N, Q	<0.01
SDI	0.10*Q	0.12*Q	0.09*Q	0.09*Q	0.02	0.05*	0.01	0.01	0.02
AWDR	0.01	0.01	0.01	0.16*Q	0.18*Q	0.18*Q	<0.01	0.06*Q	0.06*Q
Temperature#									
Mean maximum	0.05*Q	0.06*Q	0.10*Q	0.11*N	0.06*N	0.08*N	0.07*N	0.11*N	0.11*N
Mean minimum	0.15*Q	0.19*Q	0.20*Q	0.04*N	0.01	0.02	0.04*N	0.07*N	0.06*N
Mean	0.12*Q	0.15*Q	0.17*Q	0.08*N	0.04*N	0.05*N	0.06*N	0.10*N	0.09*N
GDD	0.02	<0.01	0.07*Q	0.04*Q	0.04*Q	0.03*Q	0.01	0.04*Q	0.01

* Significant at the $P \leq 0.05$ level.

† AWDR, abundant and well-distributed rainfall; BD, bulk density; CEC, cation exchange capacity; GDD, growing degree-day; SDI, Shannon diversity index; SOM, soil organic matter; TC, total C; TN, total N; TOC, total organic C.

‡ N, the linear part of the relationship with PMN_{an} was negative.

§ Q, these models had a quadratic relationship with PMN_{an}.

¶ NO_3–N and NH_4–N measured in treatment and at timing of PMN_{an} sampling.

\# Period used when regressing precipitation and temperature variables: for PP_{0N}, first-GDD to pre-plant sampling; $V5_{0N}$ and $V5_{180N}$, pre-plant sampling to V5 corn development stage.

leading to a larger pool of organic N available to be mineralized (Dessureault-Rompré et al., 2010; Hassink et al., 1993). There was a negative relationship between PMN_{an} and sand content because greater sand content was related to less SOM and total N (Table 5), which reduces N mineralization (Dessureault-Rompré et al., 2010). The reduced capacity of sandy soils to protect organic matter from microbial decomposition hinders the accumulation of organic N that increases PMN_{an} (Hassink et al., 1993).

The relationship between PMN_{an} and pH-water and pH-salt was similar to that of soil texture properties (average $R^2 = 0.12$) (Table 4). The pH-salt measurement had a marginally (8–14%) better relationship with PMN_{an} from the V5 soil samplings compared with pH-water, whereas their relationship was similar with PMN_{an} from the pre-plant sampling time. The relationship between both pH measurements and PMN_{an} varied by time of sampling. The PP_{0N} PMN_{an} timing had a positive linear response to increasing pH-salt and pH-water, whereas the PMN_{an} from $V5_{0N}$ and $V5_{180N}$ had a negative quadratic response below pH 6.0 and a positive quadratic response at pH $\geq$6.0. A reduction in N mineralization as pH decreased agrees with previous studies (Adams and Martin, 1984; Motavalli et al., 1995; Narteh and Sahrawat, 1997; Paul et al., 2001), whereas other investigators reported no relationship (Curtin et al., 1998; Dessureault-Rompré et al., 2010). However, there was a significant relationship between pH and the amount of mineralizable N in the Dessureault-Rompré et al. (2010) study in the first 2 wk of a 24-wk aerobic incubation. This relationship suggests that pH is more related to the labile pools of mineralizable N relative to the stable pools, indicating PMN_{an} might be measuring a more labile pool of mineralizable N.

The relationships between pre-plant and V5 soil inorganic-N and PMN_{an} were poor ($R^2 \leq 0.09$) (Table 4). Others have also reported little to no significant relationship between mineralizable N and soil inorganic-N (Fox and Piekielek, 1984; Mariano et al., 2013; Reussi Calvo et al., 2013). The poor correlation between soil inorganic-N and PMN_{an} was likely because NH_4–N nitrifies quickly, and soil NO_3–N can move deeper in the soil profile via leaching or volatilize via denitrification. Leaching and denitrification are dependent on weather and soil management practices (Divito et al., 2011) that varied across sites and years in our study and may be the cause of the low correlation between PMN_{an} and inorganic-N. Because inorganic-N was not a good predictor of PMN_{an}, these measurements will not be included in the remaining discussions regarding soil properties unless explicitly mentioned.

Relationship between Anaerobic Potentially Mineralizable N and Weather Prior to Soil Sampling

When relating PMN_{an} from PP_{0N} to weather conditions before the soil sampling, the weather conditions during the 30 d before PP_{0N} had a greater partial R^2 in two of the three incubation times and a greater average partial R^2 (0.12) across all three incubation times relative to the first-GDD to PP_{0N} time interval (partial $R^2 = 0.09$; data not shown). For PMN_{an} from $V5_{0N}$ and $V5_{180N}$, the weather conditions during the PP_{0N} to V5 (0.09) time interval had the strongest relationship, as measured by partial R^2 (averaged across all three incubation lengths) followed by first-GDD of the year to V5 (0.07), 30 d before PP_{0N} to V5 (0.03), and 30 d before V5 (0.05) time intervals (data not shown). Based on these analyses, we present only weather data for the 30 d before PP_{0N} time interval for PMN_{an} from PP_{0N} and the PP_{0N} to V5 time interval for PMN_{an} from $V5_{0N}$ and $V5_{180N}$ when relating precipitation and temperature measurements to PMN_{an}.

Excluding GDD, temperature variables from the 30 d before PP_{0N} interval had the best relationships with PMN_{an} from PP_{0N} ($R^2 \leq 0.20$), whereas all temperature variables from the PP_{0N} to V5 period had a slightly weaker relationship with PMN_{an} from $V5_{0N}$ and $V5_{180N}$ ($R^2 \leq 0.11$) (Table 4). There was a negative relationship between temperature and each PMN_{an} sample timing and N rate. This negative relationship likely illustrates that, with warmer temperatures, greater mineralization of easily mineralizable materials may have occurred early in the season (before V5) (Kuzyakova et al., 2006), leaving more recalcitrant materials for mineralization from samples obtained at the V5 soil sample timing. The SDI was the only precipitation variable that had a significant relationship with PMN_{an} from PP_{0N} ($R^2 = 0.09$ to 0.12), whereas the sum of precipitation ($R^2 \leq 0.16$), AWDR ($R^2 \leq 0.18$), maximum and mean precipitation ($R^2 \leq 0.11$), and SDI variables ($R^2 \leq 0.09$) had relationships with PMN_{an} from $V5_{0N}$ and $V5_{180N}$ (Table 4). The relationship between PMN_{an} and the

Table 5. Pearson correlation coefficients of soil properties.

Variable†	% Clay	% Silt	CEC	TC	TOC	SOM	TN	C/N	pH-salt	pH-water	BD-Measured	BD-Saxton
% Sand	−0.66*	−0.90*	−0.54*	−0.32*	−0.36*	−0.49*	−0.42*	0.06	0.11*	0.13*	0.54*	0.72*
% Clay	–	0.27*	0.91*	0.60*	0.63*	0.67*	0.62*	0.40*	0.27*	0.07	−0.61*	−0.75*
% Silt		–	0.17*	0.06	0.09	0.24*	0.18*	−0.31*	−0.27*	−0.21*	−0.34*	−0.49*
CEC			–	0.81*	0.84*	0.84*	0.81*	0.57*	0.34*	0.21*	−0.69*	−0.72*
TC				–	0.98*	0.93*	0.96*	0.60*	0.39*	0.32*	−0.71*	−0.64*
TOC					–	0.97*	0.98*	0.63*	0.32*	0.25*	−0.73*	−0.69*
SOM						–	0.97*	0.54*	0.18*	0.12	−0.74*	−0.76*
TN							–	0.49*	0.27*	0.21*	−0.74*	−0.71*
C/N								–	0.35*	0.25*	−0.39*	−0.35*
pH-salt									–	0.92*	−0.20*	−0.03
pH-water										–	−0.13	0.08
BD-measured											–	0.72*

* Significant at the 0.05 probability level.

† BD, bulk density; CEC, cation exchange capacity; SOM, soil organic matter; TC, total C; TN, total N; TOC, total organic C.

sum of precipitation and AWDR was positive because greater uniformity in precipitation can stimulate N mineralization by consistently rewetting the soil (Kuzyakov et al., 2000; Murphy et al., 1998; Wu et al., 2008). These results indicate that the quantity and evenness of precipitation are important for increasing N mineralization, but both variables were similarly related to PMN_{an}.

Temperature ($R^2 \leq 0.20$) and precipitation ($R^2 \leq 0.18$) variables overall had weaker relationships with PMN_{an} compared with soil properties ($R^2 \leq 0.40$) (Table 4). These relationships agree with the findings from Dessureault-Rompré et al. (2010). Soil properties may be more important because they influence the size and quality of the organic N pool, which in turn affects the amount and rate of N mineralization (Gentile et al., 2011; Gil and Fick, 2001; Mazzilli et al., 2014; Sierra, 1992). Also, because soil properties are partially the result of long-term weather conditions (Cabrera et al., 2005; Franzluebbers et al., 2001; Kuzyakov et al., 2000), soils may already integrate the effects of weather on PMN_{an}. The fact that soil properties have the best relationship with PMN_{an} is advantageous because these properties, unlike weather, are spatially and temporally more stable, providing consistency in potential mineralization estimates over years. Because PMN_{an} has been strongly related to microbial biomass and respiration (Doran, 1987; Franzluebbers et al., 2000; Myrold, 1987; Schomberg et al., 2009), it is possible that the remaining variability of PMN_{an} not explained by soil and weather conditions in our study may be explained by biological processes. However, because the focus of this study was to determine the relationship between soil and weather conditions and PMN_{an}, we can only speculate on the effect of microbial population on PMN_{an}.

Anaerobic Potentially Mineralizable N Prediction

Mean R^2 values for regression models using soil properties (including soil NO_3–N and NH_4–N) and precipitation and temperature prior to soil sampling to predict PMN_{an} were 0.57 at PP_{0N}, 0.49 at $V5_{0N}$, and 0.50 at $V5_{180N}$ when averaged across four variable selection methods (Stepwise, Forward, Backward, and Lowest CP; data not shown). These variable selection methods most often included one or more soil properties and at least one precipitation variable. The following variables were selected to predict PMN_{an} >50% of the time: percent sand, bulk density (measured and Saxton), total organic C, SOM, total N, cation exchange capacity, pH-water, NO_3–N from 0 to 30 cm, mean precipitation, SDI, AWDR, mean temperature, and GDD. Other studies also found strong relationships when selecting one or more of these variables to predict mineralizable N (Dessureault-Rompré et al., 2010, 2015; Hassink, 1994; Schomberg et al., 2009).

The stepwise variable selection method alone was used to determine the order in which variables were selected and how much PMN_{an} variability each soil and weather measurement explained. The first variable selected to predict any of the PMN_{an} values was either total N, bulk density-Saxton, total C, total organic C, or SOM (Table 6). The first variable selected through the stepwise selection method accounted for 57% of the total R^2, on average. All other variables selected and added to the model had a partial $R^2 \leq 0.14$ when averaged across lengths within incubation length within each sample timing and N rate treatment. The soil property variables contributed the most to the total R^2 (83% of R^2), followed by precipitation (15% of R^2) and temperature (4% of R^2), when averaged across all treatments. Other researchers have observed similar findings where soil properties are the strongest predictors of potentially mineralizable N and where regression equations predicting mineralizable N normally include an estimate of SOM, soil texture, and climate (Dessureault-Rompré et al., 2010, 2015; Schomberg et al., 2009). Our results, as well as those cited here, show the strong influence soil properties have on PMN_{an}, with precipitation prior to soil sampling being a secondary influence and all temperature variables prior to soil sampling having a minor influence.

The variables within each of the soil properties, precipitation, and temperature categories were often strongly correlated (Tables 5; Supplemental Tables S1–S5). Collinearity tends to lead to the selection of typically only one variable from a group of strongly correlated variables during the selection process. When a selected variable was replaced with another variable with which it was strongly correlated ($R > 0.60$), the R^2 value for the model only decreased up to 0.15 and increased up to 0.01 for soil properties (including soil NO_3–N and NH_4–N), decreased up to 0.12 for precipitation, and decreased up to 0.03 and increased up to 0.04 for temperature variables (data not shown). This result demonstrates that many variables can be used to obtain similar estimates of PMN_{an}. This can be advantageous in situations where existing databases have a limited number of variables to choose from. For example, total N or bulk density was the first variable selected by Stepwise to predict PMN_{an} 66% of the time when averaged across all treatments, but farmers do not commonly test for these variables. However, SOM is routinely measured and can be used instead of total N or bulk density to predict PMN_{an} with similar accuracy. Understanding what commonly available soil and weather variables are useful to predict PMN_{an} may improve the utility of PMN_{an} as a tool to manage N fertilizer rates more effectively.

Predictability of PMN_{an} from PP_{0N} (R^2 = 0.54–0.69) at each incubation length was greater than predicting PMN_{an} from either V5 N rate (R^2 = 0.43–0.59) (Table 6). Increasing incubation time beyond 7 d improved R^2 by an average of 8%, with a high of 16% coming from the V5 sample timing after N fertilizer was applied at planting ($V5_{180N}$). The reduced predictability of PMN_{an} after N fertilizer addition with the 7-d incubation time demonstrates the difficulty of predicting N mineralization after N fertilization, which agrees with the findings of others (Fernández et al., 2017; Kuzyakova et al., 2006; Ma et al., 1999). This reduced predictability may be because the quality of organic matter varied among experimental sites in this study (Table 2), and this interacts with the influence of N fertilizer on N mineralization (Chen et al., 2014; Jenkinson et al., 1985; Kuzyakova et al., 2006).

Corn growers in the US Midwest region can currently modify their N fertilizer rate based on soil tests obtained before N fertilizer application. Our results indicate that using PMN_{an}

from soil samples taken before N fertilization may reduce the effectiveness of PMN_{an} as an N management tool. However, using 14- or 28-d incubation periods may overcome this challenge because the predictability of PMN_{an} after fertilization ($V5_{180N}$) from a 14- and 28-d incubation period using soil and weather conditions was more similar to PMN_{an} without N fertilization. The use of this longer incubation period might be important in obtaining better estimates of N fertilizer needs.

CONCLUSIONS

Greater distribution of precipitation and warmer temperatures early in the season prior to sampling resulted in greater PMN_{an}, but, more importantly, soil properties directly or indirectly associated with greater SOM also increased PMN_{an}. The strength of the relationships between soil properties and PMN_{an} from PP_{0N}, $V5_{0N}$, and $V5_{180N}$ varied by ≤10%. Although for weather conditions before sampling, the delayed V5 samplings had more relationships compared with the preplant timing likely because weather conditions had more time to influence N mineralization. Furthermore, although weather is often considered an influential factor on PMN_{an}, we showed that soil properties (except for inorganic N) had better relationships with PMN_{an}. The fact that soil properties have the strongest relationship with PMN_{an} may be important in the development of N management tools because many soil properties are more stable from year to year than weather conditions.

The relationships between PMN_{an} and soil properties and weather conditions alone were slightly weak ($R^2 \leq 0.40$) but greatly increased when soil and weather conditions were used together to predict PMN_{an} ($R^2 \leq 0.69$). These results emphasize the need to better quantify soil properties and their interactive effect with precipitation and temperature to better understand their influence on mineralizable N and to potentially improve N management using PMN_{an}. Total N, bulk density-Saxton, total C, total organic C, or SOM was the first variable selected by the Stepwise selection process to predict PMN_{an} and provided the greatest contribution to R^2. Because SOM is routinely measured and can be used instead of these other measurements without

Table 6. Partial R^2 and total R^2 values for the prediction of the anaerobic potentially mineralizable N soil test (PMN_{an}) from soil samples obtained before planting and N fertilizer application (PP_{0N}) and at the V5 development stage where zero ($V5_{0N}$) or 180 kg N ha^{-1} ($V5_{180N}$) was applied at planting and incubated for 7, 14, and 28 d as a function of soil properties, precipitation, and temperature variables across 32 site-years selected by the Stepwise selection method. Bold numbers indicate the soil or weather condition that was selected first by the Stepwise selection method and contributed the most to the total explained variability.

	PP_{0N}			$V5_{0N}$			$V5_{180N}$		
Variable†	7 d	14 d	28 d	7 d	14 d	28 d	7 d	14 d	28 d
	Partial R^2								
Soil physical characteristics									
% Sand	0.04	0.08	0.05	–	–	–	–	–	–
% Clay	–	–	–	0.03	–	–	–	–	0.03
BD-Saxton	–	–	0.01	**0.20**	**0.24**	**0.35**	0.06	0.09	0.02
Soil chemical characteristics									
TC	–	–	–	–	–	–	**0.24**	–	–
TOC	–	–	0.05	–	–	–	0.04	0.02	**0.37**
SOM	–	–	–	–	–	0.01	0.03	**0.29**	–
TN	**0.33**	**0.30**	**0.40**	–	–	0.03	–	–	–
CEC	–	–	–	–	–	–	0.03	–	–
pH-salt	–	–	–	0.14	0.05	0.03	–	–	0.05
pH-water	0.04	0.02	0.02	–	–	–	–	–	–
Inorganic N‡									
NH_4–N§ 0–30 cm	–	–	–	–	–	0.03	–	–	–
NO_3–N§ 0–30 cm	0.03	–	–	–	–	–	0.05	0.03	–
NO_3–N 0–90 cm	–	0.04	–	–	–	–	–	–	–
Precipitation§									
Max	–	0.01	0.02	–	–	–	–	–	–
Mean	–	–	–	–	–	–	0.07	0.04	–
SDI	0.08	0.12	0.07	0.07	–	–	0.03	0.04	–
AWDR	–	–	–	–	0.10	0.08	–	–	–
Temperature§									
Mean maximum	–	0.03	0.03	–	–	–	–	–	–
Mean minimum	–	–	–	–	–	–	–	0.05	–
Mean	–	–	–	–	–	–	–	–	0.05
GDD	–	–	–	–	–	–	0.01	–	0.02
	–Total R^2–								
	0.54	0.57	0.69	0.52	0.57	0.56	0.43	0.59	0.51

† AWDR, abundant and well-distributed rainfall; BD, bulk density; CEC, cation exchange capacity; GDD, growing degree-day; SDI, Shannon diversity index; SOM, soil organic matter; TC, total C; TN, total N; TOC, total organic C.

‡ Ammonium and nitrate measured in treatment and at timing of PMN_{an} sampling.

§ Period used when regressing precipitation and temperature variables: PP_{0N}, 30-d before pre-plant sampling; $V5_{0N}$ and $V5_{180N}$, pre-plant sampling to V5 corn development stage.

substantially affecting PMN_{an} predictability, this parameter may be the best suited for practical considerations. The predictability of PMN_{an} from 7-d incubations decreased when delaying soil sampling from preplant to V5 regardless of N fertilization but increased with longer incubations, with a greater increase coming when fertilized at planting ($V5_{180N}$). This result is important because most producers fertilize their fields before the V5 development stage and indicates the potential of PMN_{an} from longer incubation periods being able to better estimate N mineralization when N fertilizer is applied. These results demonstrate that soil and weather conditions are important when predicting PMN_{an} ($R^2 \leq 0.69$) and need to be considered in future research working to further improve PMN_{an} predictability and utility.

SUPPLEMENTAL MATERIAL

The supplemental material includes five additional tables. These tables contain Pearson correlation coefficients of soil nitrate-N and ammonium-N measurements from different sample timings and N fertilizer rates. In addition, there are tables with Pearson correlation coefficients of precipitation and temperature variables from the time period of 30-d before pre-plant to pre-plant sample timing and from the pre-plant sample timing to the V5 corn development stage."

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REFERENCES

Adams, F., and J.B. Martin. 1984. Liming effect on nitrogen use efficiency. In: R.D. Hauck, editor, Nitrogen in crop production. ASA, CSSA, and SSSA, Madison, WI. p. 417–426.

Beare, M.H., E.G. Gregorich, and P. St-Georges. 2009. Compaction effects on CO_2 and N_2O production during drying and rewetting of soil. Soil Biol. Biochem. 41:611–621. doi:10.1016/j.soilbio.2008.12.024

Beyaert, R.P., and R.P. Voroney. 2011. Estimation of decay constants for crop residues measured over 15 years in conventional and reduced tillage systems in a coarse-textured soil in southern Ontario. Can. J. Soil Sci. 91:985–995. doi:10.4141/cjss2010-055

Bronikowski, A., and C. Webb. 1996. A critical examination of rainfall variability measures used in behavioral ecology studies. Behav. Ecol. Sociobiol. 39:27–30. doi:10.1007/s002650050263

Bundy, L.G., and J.J. Meisinger. 1994. Nitrogen availability indices. In: R.W. Weaver, editor, Methods of soil analysis: Biochemical and microbial properties. SSSA Monogr. 5. SSSA, Madison, WI. p. 951–984.

Cabrera, M.L., D.E. Kissel, and M.F. Vigil. 2005. Nitrogen mineralization from organic residues: Research opportunities. J. Environ. Qual. 34:75–79. doi:10.2134/jeq2005.0075

Carrington, E.M., P.J. Hernes, R.Y. Dyda, A.F. Plante, and J. Six. 2012. Biochemical changes across a carbon saturation gradient: Lignin, cutin, and suberin decomposition and stabilization in fractionated carbon pools. Soil Biol. Biochem. 47:179–190. doi:10.1016/j.soilbio.2011.12.024

Chen, R., M. Senbayram, S. Blagodatsky, O. Myachina, K. Dittert, X. Lin, E. Blagodatskaya, and Y. Kuzyakov. 2014. Soil C and N availability determine the priming effect: Microbial N mining and stoichiometric decomposition theories. Glob. Change Biol. 20:2356–2367. doi:10.1111/gcb.12475

Christensen, N.W., and M.E. Mellbye. 2006. Validation and recalibration of a soil test for mineralizable nitrogen. Commun. Soil Sci. Plant Anal. 37:2199–2211. doi:10.1080/00103620600817416

Christensen, N.W., M.H. Qureshi, D.M. Baloch, and R.S. Karow. 1999. Assessing nitrogen mineralization in a moist xeric environment. In: Proc. Western Nutrient Mgmt. Conf. Potash & Phosphate Institute, Salt Lake City, UT. p. 83–90.

Clark, J.D. 2018. Improving nitrogen management with the anaerobic potentially mineralizable nitrogen test. Ph.D. diss. Univ. of Minnesota-Twin Cities.

Conde, E., M. Cardenas, A. Ponce-Mendoza, M.L. Luna-Guido, C. Cruz-Mondragón, and L. Dendooven. 2005. The impacts of inorganic nitrogen application on mineralization of ^{14}C-labeled maize and glucose, and on priming effect in saline alkaline soil. Soil Biol. Biochem. 37:681–691. doi:10.1016/j.soilbio.2004.08.026

Culman, S.W., S.S. Snapp, J.M. Green, and L.E. Gentry. 2013. Short- and long-term labile soil carbon and nitrogen dynamics reflect management and predict corn agronomic performance. Agron. J. 105:493–502. doi:10.2134/agronj2012.0382

Curtin, D., C.A. Campbell, and A. Jalil. 1998. Effects of acidity on mineralization: pH-dependence of organic matter mineralization in weakly acidic soils. Soil Biol. Biochem. 30:57–64. doi:10.1016/S0038-0717(97)00094-1

Dessureault-Rompré, J., B.J. Zebarth, D.L. Burton, and A. Georgallas. 2015. Predicting soil nitrogen supply from soil properties. Can. J. Soil Sci. 95:63–75. doi:10.4141/cjss-2014-057

Dessureault-Rompré, J., B.J. Zebarth, D.L. Burton, M. Sharifi, J. Cooper, C.A. Grant, and C.F. Drury. 2010. Relationships among mineralizable soil nitrogen, soil properties, and climatic indices. Soil Sci. Soc. Am. J. 74:1218–1227. doi:10.2136/sssaj2009.0213

Divito, G.A., H.R.S. Rozas, H.E. Echeverría, G.A. Studdert, and N. Wyngaard. 2011. Long term nitrogen fertilization: Soil property changes in an Argentinean Pampas soil under no tillage. Soil Tillage Res. 114:117–126. doi:10.1016/j.still.2011.04.005

Doran, J.W. 1987. Microbial biomass and mineralizable nitrogen distributions in no-tillage and plowed soils. Biol. Fertil. Soils 5:68–75. doi:10.1007/BF00264349

Fernández, F.G., K.P. Fabrizzi, and S.L. Naeve. 2017. Corn and soybean's season-long in-situ nitrogen mineralization in drained and undrained soils. Nutr. Cycl. Agroecosyst. 107:33–47. doi:10.1007/s10705-016-9810-1

Fox, R.H., and W.P. Piekielek. 1984. Relationships among anaerobically mineralized nitrogen, chemical indexes, and nitrogen availability to corn. Soil Sci. Soc. Am. J. 48:1087–1090. doi:10.2136/sssaj1984.03615995004800050027x

Franzluebbers, A.J., R.L. Haney, C.W. Honeycutt, M.A. Arshad, H.H. Schomberg, and F.M. Hons. 2001. Climatic influences on active fractions of soil organic matter. Soil Biol. Biochem. 33:1103–1111. doi:10.1016/S0038-0717(01)00016-5

Franzluebbers, A.J., R.L. Haney, C.W. Honeycutt, H.H. Schomberg, and F.M. Hons. 2000. Flush of carbon dioxide following rewetting of dried soil relates to active organic pools. Soil Sci. Soc. Am. J. 64:613–623. doi:10.2136/sssaj2000.642613x

Franzluebbers, A.J., R.L. Haney, F.M. Hons, and D.A. Zuberer. 1996. Active fractions of organic matter in soils with different texture. Soil Biol. Biochem. 28:1367–1372. doi:10.1016/S0038-0717(96)00143-5

Gelderman, R.H., and D. Beegle. 2015. Nitrate-nitrogen. In: M. Nathan and R. Gelderman, editors, Recommended chemical soil test procedures for the North Central Region. North Central Regional Res. Publ. no. 221 (revised Aug. 2015). Missouri Agric. Exp. Stn, Columbia. p. 5.1–5.4.

Gentile, R., B. Vanlauwe, and J. Six. 2011. Litter quality impacts short- but not long-term soil carbon dynamics in soil aggregate fractions. Ecol. Appl. 21:695–703. doi:10.1890/09-2325.1

Gil, J.L., and W.H. Fick. 2001. Soil nitrogen mineralization in mixtures of eastern gamagrass with alfalfa. Agron. J. 93:902–910. doi:10.2134/agronj2001.934902x

Grandy, A.S., and J.C. Neff. 2008. Molecular C dynamics downstream: The biochemical decomposition sequence and its impact on soil organic matter structure and function. Sci. Total Environ. 404(2–3):297–307. doi:10.1016/j.scitotenv.2007.11.013

Hassink, J. 1994. Effects of soil texture and grassland management on soil organic C and N and rates of C and N mineralization. Soil Biol. Biochem. 26:1221–1231. doi:10.1016/0038-0717(94)90147-3

Hassink, J., L.A. Bouwman, K.B. Zwart, J. Bloem, and L. Brussaard. 1993. Relationships between soil texture, physical protection of organic matter, soil biota, and C and N mineralization in grassland soils. Geoderma 57:105–128. doi:10.1016/0016-7061(93)90150-J

Jenkinson, D.S., R.H. Fox, and J.H. Rayner. 1985. Interactions between fertilizer nitrogen and soil nitrogen- the so-called "priming" effect. J. Soil Sci. 36:425–444. doi:10.1111/j.1365-2389.1985.tb00348.x

Keeney, D.R., and J.M. Bremner. 1966. Comparison and evaluation of laboratory methods of obtaining an index of soil nitrogen availability. Agron. J. 58:498–503. doi:10.2134/agronj1966.00021962005800050013x

Khan, S.A., R.L. Mulvaney, and R.G. Hoeft. 2001. A simple soil test for detecting sites that are nonresponsive to nitrogen fertilization. Soil Sci. Soc. Am. J. 65:1751–1760. doi:10.2136/sssaj2001.1751

Kitchen, N.R., J.F. Shanahan, C.J. Ransom, C.J. Bandura, G.M. Bean, J.J. Camberato, et al. 2017. A public-industry partnership for enhancing corn nitrogen research and datasets: Project description, methodology, and outcomes. Agron. J. 109:2371–2388. doi:10.2134/agronj2017.04.0207

Kuo, S., and U.M. Sainju. 1998. Nitrogen mineralization and availability of mixed leguminous and non-leguminous cover crop residues in soil. Biol. Fertil. Soils 26:346–353. doi:10.1007/s003740050387

Kuzyakova, I.F., F.R. Turyabahika, and K. Stahr. 2006. Time series analysis and mixed models for studying the dynamics of net N mineralization in a soil catena at Gondelsheim (S-W Germany). Geoderma 136:803–818. doi:10.1016/j.geoderma.2006.06.003

Kuzyakov, Y., J.K. Friedel, and K. Stahr. 2000. Review of mechanisms and quantification of priming effects. Soil Biol. Biochem. 32:1485–1498. doi:10.1016/S0038-0717(00)00084-5

Ladd, J.N., M. Van Gestel, L.J. Monrozier, and M. Amato. 1996. Distribution of organc 14C and 15N in particle-size fractions of soils incubated with 14C, 15N-lableled glcose/NH4, and legume and wheat straw residues. Soil Biol. Biochem. 28(7):893–905. doi:10.1016/0038-0717(96)00069-7

Ma, B.L., L.M. Dwyer, and E.G. Gregorich. 1999. Soil nitrogen amendment effect on seasonal nitrogen mineralization and nitrogen cycling in maize production. Agron. J. 91:1003–1009. doi:10.2134/agronj1999.9161003x

Mallows, C.L. 1973. Some comments on Cp. Technometrics 15:661–675.

Mariano, E., P.C.O. Cesar, J.M. Leite, M. Xavier, V. Megda, R. Otto, and H.C.J. Franco. 2013. Incubation methods for assessing mineralizable nitrogen in soils under sugarcane. Rev. Bras. Cienc. Solo 37:450–461. doi:10.1590/S0100-06832013000200016

Mazzilli, S.R., A.R. Kemanian, O.R. Ernst, R.B. Jackson, and G. Pineiro. 2014. Priming of soil organic carbon decomposition induced by corn compared to soybean crops. Soil Biol. Biochem. 75:273–281. doi:10.1016/j.soilbio.2014.04.005

Melkonian, J., H.J. Poffenbarger, S.B. Mirsky, and M.R. Ryan. 2017. Estimating nitrogen mineralization from cover crop mixtures using the precision nitrogen management model. Agron. J. 109:1944–1959. doi:10.2134/agronj2016.06.0330

Mikha, M.M., C.W. Rice, and J.G. Benjamin. 2006. Estimating soil mineralizable nitrogen under different management practices. Soil Sci. Soc. Am. J. 70:1522–1531. doi:10.2136/sssaj2005.0253

Motavalli, P.P., C.A. Palm, W.J. Parton, E.T. Elliott, and S.D. Frey. 1995. Soil pH and organic C dynamics in tropical forest soils: Evidence from laboratory and simulation studies. Soil Biol. Biochem. 27:1589–1599. doi:10.1016/0038-0717(95)00082-P

Murphy, D.V., G.P. Sparling, I.R.P. Fillery, A.M. McNeill, and P. Braunberger. 1998. Mineralization of soil organic nitrogen and microbial respiration after simulated summer rainfall events in an agricultural soil. Aust. J. Soil Res. 36:231–246. doi:10.1071/S97043

Myrold, D.D.D. 1987. Relationship between microbial biomass nitrogen and a nitrogen availability index. Soil Sci. Soc. Am. J. 51:1047–1049. doi:10.2136/sssaj1987.03615995005100040040x

Narteh, L.T., and K.L. Sahrawat. 1997. Potentially mineralizable nitrogen in West African lowland rice soils. Geoderma 76:145–154. doi:10.1016/S0016-7061(96)00097-3

O'Leary, M., G. Rehm, and M. Schmitt. 2002. Understanding nitrogen in soils. Univ. of Minnesota Extension, St Paul.

Orcellet, J., N.I. Reussi Calvo, H.R. Sainz Rozas, N. Wyngaard, and H.E. Echeverría. 2017. Anaerobically incubated nitrogen improved nitrogen diagnosis in corn. Agron. J. 109:291–298. doi:10.2134/agronj2016.02.0115

Parton, W., W.L. Silver, I.C. Burke, L. Grassens, M.E. Harmon, et al. 2007. Global-scale similarities in nitrogen release patterns during long-term decomposition. Science 315:361–364. doi:10.1126/science.1134853

Paul, K., S. Black, and M. Conyers. 2001. Development of nitrogen mineralisation gradients through surface soil depth and their influence on surface soil pH. Plant Soil 234:239–246. doi:10.1023/A:1017904613797

Randall, G.W., and J.A. Vetsch. 2005. Nitrate losses in subsurface drainage from a corn-soybean rotation as affected by fall and spring application of nitrogen and nitrapyrin. J. Environ. Qual. 34:590–597. doi:10.2134/jeq2005.0590

Reussi Calvo, N.I., H. Sainz Rozas, H. Echeverría, and A. Berardo. 2013. Contribution of anaerobically incubated nitrogen to the diagnosis of nitrogen status in spring wheat. Agron. J. 105:321–328. doi:10.2134/agronj2012.0287

Rhine, E.D., R.L. Mulvaney, E.J. Pratt, and G.K. Sims. 1998. Improving the Berthelot reaction for determining ammonium in soil extracts and water. Soil Sci. Soc. Am. J. 62:473–480. doi:10.2136/sssaj1998.03615995006200020026x

Ribaudo, M., J. Delgado, L. Hansen, M. Livingston, R. Mosheim, and J. Williamson. 2011. Nitrogen in agricultural systems: Implications for conservation policy. USDA, Washington, DC.

Ritchie, S.W., J.J. Hanway, and G.O. Benson. 1996. How a corn plant develops. Iowa State Univ., Ames.

Ros, G.H., E.J.M. Temminghoff, and E. Hoffland. 2011. Nitrogen mineralization: A review and meta-analysis of the predictive value of soil tests. Eur. J. Soil Sci. 62:162–173. doi:10.1111/j.1365-2389.2010.01318.x

Saha, U.K., L. Sonon, and B.K. Biswas. 2018. A comparison of diffusion-conductimetric and distillagion-titration methods in analyazing ammonium- and nitrate-nitrogen in the KCl-extracts of Georgia soils. Commun. Soil Sci. Plant Anal. 49:63–75. doi:10.1080/00103624.2017.1421647

Sainz Rozas, H., P.A. Calvino, H.E. Echeverría, P.A. Barbieri, and M. Redolatti. 2008. Contribution of anaerobically mineralized nitrogen to the reliability of planting or presidedress soil nitrogen test in maize. Agron. J. 100:1020–1025. doi:10.2134/agronj2007.0077

Saxton, K.E., and W.J. Rawls. 2006. Soil water characteristic estimates by texture and organic matter for hydrologicsolutions. Soil Sci. Soc. Am. J. 70:1569–1578. doi:10.2136/sssaj2005.0117

Schomberg, H.H., S. Wietholter, T.S. Griffin, D.W. Reeves, M.L. Cabrera, D.S. Fisher, et al. 2009. Assessing indices for predicting potential nitrogen mineralization in soils under different management systems. Soil Sci. Soc. Am. J. 73:1575–1586. doi:10.2136/sssaj2008.0303

Sierra, J. 1992. Relationship between mineral N content and N mineralization rate in disturbed and undisturbed soil samples incubated under field and laboratory conditions. Aust. J. Soil Res. 30:477–492. doi:10.1071/SR9920477

Sierra, J. 1996. Nitrogen mineralisation and its error of estimation under field conditions related to the light-fraction soil organic matter. Aust. J. Soil Res. 34:755–767. doi:10.1071/SR9960755

Smith, J.L., B.L. McNeal, E.J. Owens, and G.O. Klock. 1981. Comparison of nitrogen mineralized under anaerobic and aerobic conditions for some agricultural and forest soils of Washington. Commun. Soil Sci. Plant Anal. 12:997–1009. doi:10.1080/00103628109367212

Soon, Y.K., A. Haq, and M.A. Arshad. 2007. Sensitivity of nitrogen mineralization indicators to crop and soil management. Commun. Soil Sci. Plant Anal. 38:2029–2043. doi:10.1080/00103620701548688

Stanford, G., and S.J. Smith. 1972. Nitrogen mineralization potentials of soils. Soil Sci. Soc. Am. Proc. 36:465–472. doi:10.2136/sssaj1972.03615995003600030029x

Struffert, A.M., J.C. Rubin, F.G. Fernández, and J.A. Lamb. 2016. Nitrogen management for corn and groundwater quality in Upper Midwest irrigated sands. J. Environ. Qual. 45:1557–1564. doi:10.2134/jeq2016.03.0105

Studdert, G.A., G.F. Domínguez, N. Fioriti, M.V. Cozzoli, N.V. Diovisalvi, and M.J. Eliza. 2006. Relacion entre nitrógeno anaeróbico y materia orgánica de Molisoles de Balcarce. Paper presented at: Actas XX Congreso Argentino de la Ciencia del Suelo, Salt-Jujuy, Argentina. 19–22 Sept. 2006.

Tremblay, N., Y.M. Bouroubi, C. Bélec, R.W. Mullen, N.R. Kitchen, W.E. Thomason, et al. 2012. Corn response to nitrogen is influenced by soil texture and weather. Agron. J. 104:1658–1671. doi:10.2134/agronj2012.0184

Van Veen, J.A., and P.J. Kuikman. 1990. Soil structural aspects of decomposition of organic matter by micro-organisms. Biogeochemistry 11:213–233. doi:10.1007/BF00004497

Wade, J., W.R. Horwath, and M.B. Burger. 2016. Integrating soil biological and chemical indices to predict net nitrogen mineralization across California agricultural systems. Soil Sci. Soc. Am. J. 80:1675–1687. doi:10.2136/sssaj2016.07.0228

Waring, S.A., and J.M. Bremner. 1964. Ammonium production in soil under waterlogged conditions as an index of nitrogen availability. Nature 201:951–952 [erratum: 203:819]. doi:10.1038/201951a0

Williams, J.D., C.R. Crozier, J.G. White, R.P. Sripada, and D.A. Crouse. 2007. Comparison of soil nitrogen tests for corn fertilizer recommendations in the humid southeastern USA. Soil Sci. Soc. Am. J. 71:171–180. doi:10.2136/sssaj2006.0057

Wu, T.Y., B.L. Ma, and B.C. Liang. 2008. Quantification of seasonal soil nitrogen mineralization for corn production in eastern Canada. Nutr. Cycl. Agroecosyst. 81:279–290. doi:10.1007/s10705-007-9163-x

Yost, M.A., J.A. Coulter, M.P. Russelle, C.C. Sheaffer, and D.E. Kaiser. 2012. Alfalfa nitrogen credit to first-year corn: Potassium, regrowth, and tillage timing effects. Agron. J. 104:953–962. doi:10.2134/agronj2011.0384